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Coupled interactions of the monsoons

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[1] A case is made to show that all continental summer monsoon regions of the globe are manifestations of strong, coupled ocean-land-atmosphere interactions. It is shown from observations that the auto-decorrelation time of the daily rainfall in the summer monsoon regions is usually in excess of 3 days. This characteristic feature of the monsoon rainfall is well simulated in a global coupled ocean-land-atmosphere model. The atmospheric general circulation model component integrations of the same coupled model forced with observed SST show a distinctly shorter auto-decorrelation time of the daily monsoon precipitation. An obvious conclusion is that air-sea coupling is essential for this feature of the monsoon rainfall to be simulated. But through additional diagnostic calculations it is also shown that the robust land-atmosphere interactions over these regions also contribute to the lengthening of the auto-decorrelation time of the daily continental summer monsoon rainfall. **Citation:** Misra, V. (2008), Coupled interactions of the monsoons, *Geophys. Res. Lett.*, *35*, L12705, doi:10.1029/2008GL033562.

1. Introduction

[2] Monsoon signifies a strong annual cycle with seasonal reversal of winds. Several regional monsoons have been identified that essentially relate to this feature of the strong annual cycle [*Trenberth*, 2005, and references therein]. In the context of the Asian-Australian monsoon there is evidence to suggest that it is a coupled ocean-land-atmosphere phenomenon [*Webster et al.*, 1998; *Wang*, 2005, and references therein]. On the other hand in relation to the other regional monsoons like the North American, South American and the West African monsoons this concept is still under investigation [*Saha et al.*, 2005; *Nobre et al.*, 2006; *Cook and Vizy*, 2006; *Joly et al.*, 2007].

[3] Despite the large seasonal variations of the monsoons, the monsoon prediction skills at seasonal to interannual scales have been rather small [*Kang and Shukla*, 2005; *Krishnamurti et al.*, 2005; *Nobre et al.*, 2006; *Cook and Vizy*, 2006; *Thiaw and Mo*, 2005]. The overbearing influence of the internal dynamics of the atmosphere [*Kang and Shukla*, 2005], the strong scale interactions [*Krishnamurti et al.*, 2003], inadequate resolution of the climate models [*Krishnamurti et al.*, 1998], and a delicate balance of remote and local forcing [*Grimm et al.*, 2003; *Huang and Shukla*, 2007a, 2007b; *Douville et al.*, 2006], are some of the main reasons for the rather low predictability of the monsoons by the current climate models.

[4] The importance of air-sea interaction on predictability at seasonal to interannual scales has been demonstrated in several studies [*Bretherton and Battisti*, 2000; *Barsugli and Battisti*, 1998; *Wang et al.*, 2005; *Wu et al.*, 2006]. These studies in general point that air-sea fluxes are not properly represented in AGCM integrations resulting in either reduced or erroneous atmospheric variability.

[5] In this study we hone in on one feature of the monsoon i.e., the relatively long auto-decorrelation (hereafter decorrelation) time of the daily monsoon precipitation. In Figures 1a and 1b we show the decorrelation time (in days) of global precipitation from the Global Offline Land Data assimilation (GOLD) [*Dirmeyer and Tan*, 2001] product. GOLD uses hybrid sets of meteorological forcing data including precipitation that have been produced for example by combining the ERA 40 reanalysis [*Uppala et al.*, 2005] with Global Precipitation Climatology Centre (GPCC) [*Rudolf et al.*, 1994] monthly precipitation estimates. Our preference to use this GOLD data set stems from its longer period of availability (1960–2002) of global daily precipitation at around 2^0 horizontal resolution. Figures 1a and 1b are qualitatively consistent with other regionally available high-resolution data sets of rain gauge precipitation.[1] Furthermore, GOLD provides land-surface state variables and fluxes consistent with the meteorological forcing (used for verification in this study). It is apparent from Figure 1a that the decorrelation time of daily precipitation is in excess of 3 days in the Boreal winter season over tropical South America, northern Australia, Southern and near equatorial Africa. Similarly in the Boreal summer season the decorrelation time is in excess of 3 days over India, China, equatorial and sub-Saharan Africa, Mexico and Southwest US.

[6] The rest of the paper is dedicated to understanding the mechanism of this feature of the monsoons. Two model integrations, integrated to several decades, one in which air-sea coupling is included and the other in which the AGCM component is forced with observed SST are compared and assessed for their decorrelation time of the daily precipitation.

2. Model Description and Experiment Design

[7] The Center for Ocean-Land-Atmosphere Studies (COLA) coupled climate model [*Misra et al.*, 2007; *Misra and Marx*, 2007] is used in this study. A brief outline of the AGCM and OGCM of the coupled model are provided in the auxiliary material. The coupled model result presented here is from a 100-year integration. The coupled mean state of the model was well spun-up before the start of the integration [*Misra and Marx*, 2007]. This experiment is

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL033562.

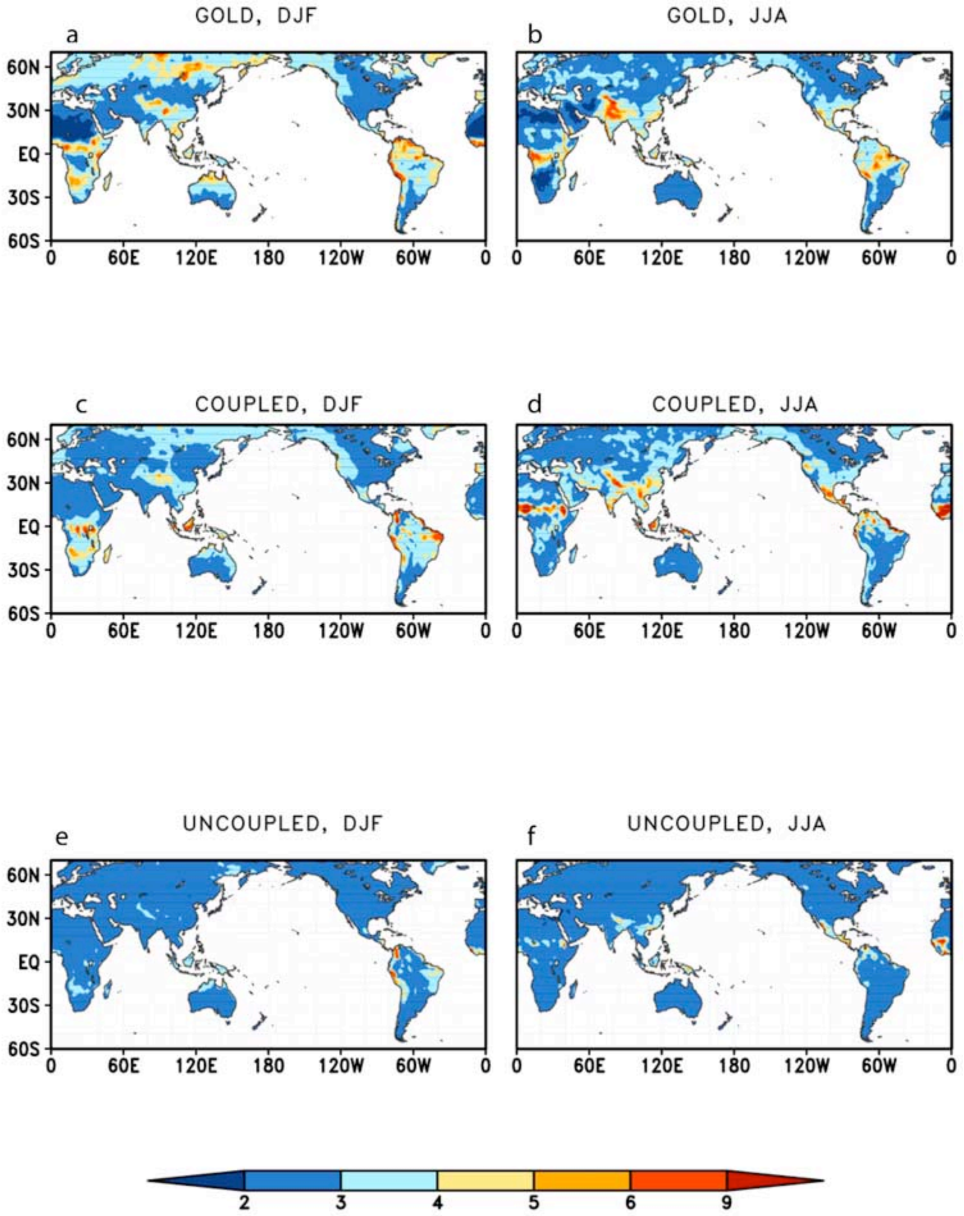

Figure 1. Decorrelation time of daily precipitation in boreal winter from (a) GOLD, (c) COUPLED, and (e) UNCOUPLED and in boreal summer from (b) GOLD, (d) COUPLED, and (f) UNCOUPLED simulations. The units are in days.

hereafter referred to as COUPLED. Similarly, the AGCM identical to that used in the COUPLED experiment is integrated for 100 years from 1901–2000 with observed SST from optimally interpolated version 2 (OI2) following *Reynolds et al.* [2002]. This experiment hereafter is called UNCOUPLED. The results are however presented from the last 50 years of both the model integrations. This is primarily because the daily data were saved for this period, which is extensively used in the following analysis.

3. Results

3.1. Role of Air-Sea Coupling

[8] In Figures 1c–1f the decorrelation time of the daily precipitation from the COUPLED and the UNCOUPLED integrations are shown for the two seasons. It is seen from Figure 1 that the COUPLED model simulates this feature far better than the UNCOUPLED version of the model. The UNCOUPLED model (Figures 1e and 1f) in the Boreal winter (summer) shows some relative lengthening of the decorrelation time of precipitation over parts of South America, northern Australia, southern Africa, and Micronesia (eastern India and China, central America and Mexico, and sub-Saharan Africa). But the COUPLED run (Figures 1c and 1d) exhibits a more reasonable decorrelation time of the summer monsoon precipitation both qualitatively and quantitatively in comparison with the GOLD data set. However, the COUPLED integration (in Figure 1c) displays model bias such as the shorter (longer) decorrelation time over northern Australia, and

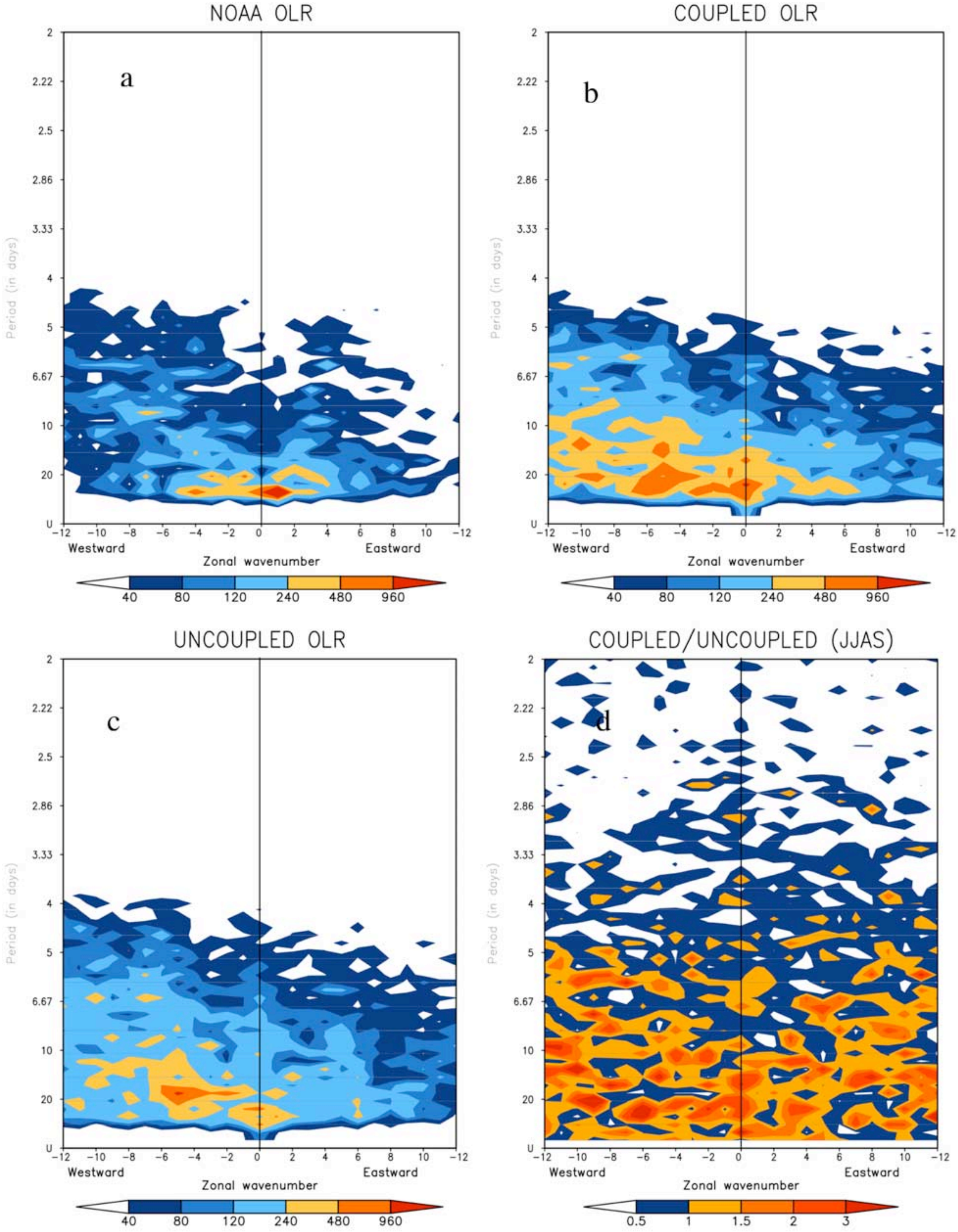

Figure 2. Wavenumber-frequency spectra averaged from 5°N–25°N for June–July–August–September season of OLR bandpass filtered for periods between 2–60 days from (a) observations [*Liebmann and Smith*, 1996], (b) COUPLED, and (c) UNCOUPLED simulations. (d) The ratio of the power spectrum of the COUPLED to the UNCOUPLED simulation. The units of power are W^2m^{-4}/cpd.

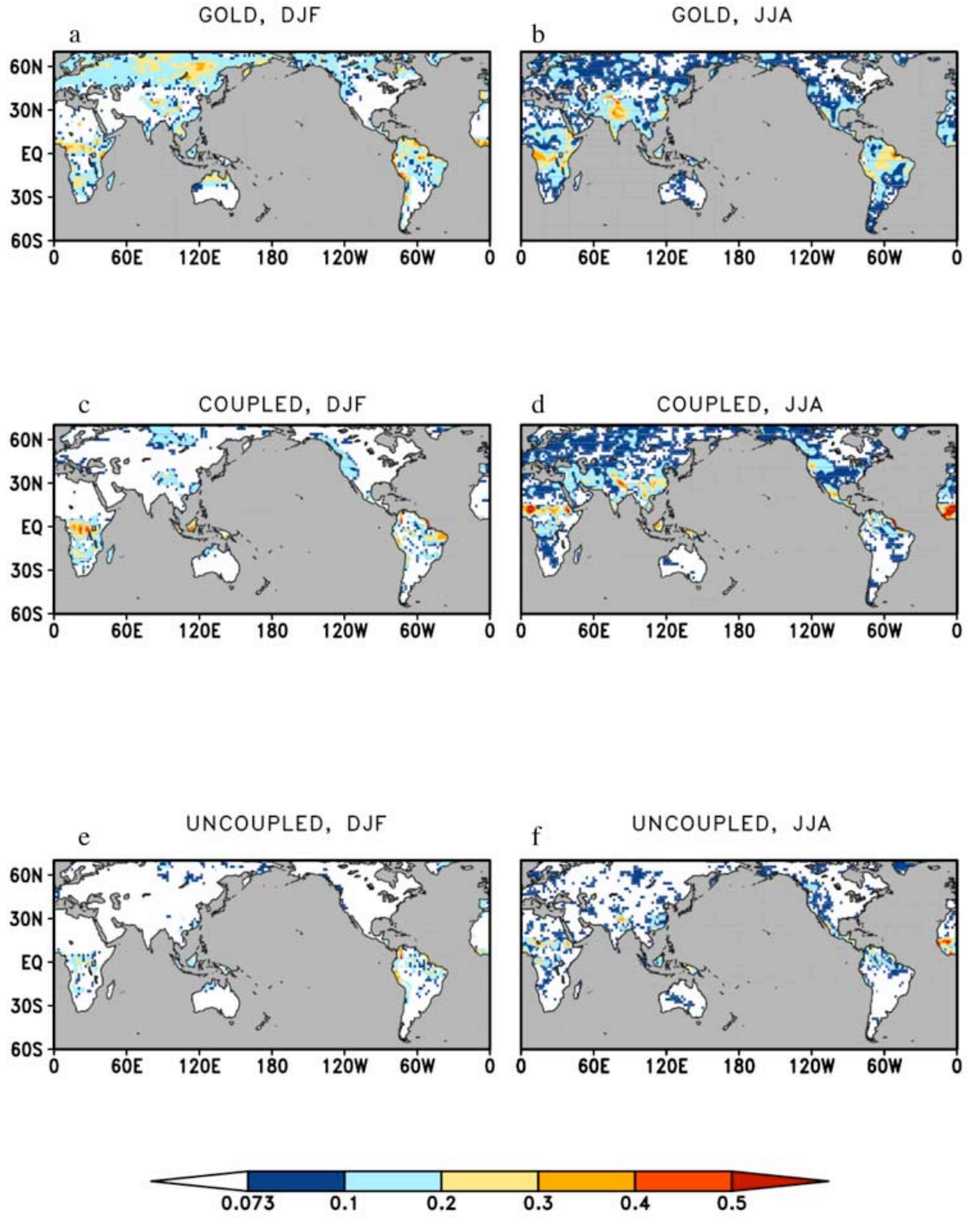

Figure 3. The correlation of twice-removed triad precipitation for winter season of DJF from (a) GOLD, (c) COUPLED, and (e) UNCOUPLED simulations and from summer season of JJA from (b) GOLD, (d) COUPLED, and (f) UNCOUPLED simulations. Only significant values at 90% confidence interval according to t-test are shaded over land.

over winter monsoons of India and China (south central Africa). Similarly, in the Boreal summer (Figure 1d) the bias of shorter (longer) decorrelation time of the winter South American monsoon (sub-Saharan Africa) is quite apparent. It is obvious then from Figure 1 that air-sea coupling is important to simulate this feature of the monsoons. This suggests that air-sea coupling extends the memory of the day-to-day precipitation events over the monsoon region. This is primarily a result of the enhancement of the sub-seasonal atmospheric variability that results in more "on-shore" precipitation over the continental monsoon region in the COUPLED simulation. This is shown in Figure 2, which shows the power spectrum of OLR from observations, the COUPLED and the UNCOUPLED simulations for the Boreal summer season averaged between 5°N–25°N (boreal summer monsoon latitudes). The power spectrum is plotted after band pass filtering the OLR through a fourth order recursive Butterworth filter between 2–60 days. Although neither of the two simulations are able to capture the strong observed intraseasonal variance (>30 days), the COUPLED simulation exhibits more variance than the UNCOUPLED at sub-seasonal (<30 days) time scales. Furthermore, the westward propagating anomalies associated with tropical disturbances in the 5–10 days range has more variance in the COUPLED simulation than in the UNCOUPLED. Likewise in the Boreal winter season the COUPLED model exhibits more sub-seasonal variance than the UNCOUPLED integration (not shown).

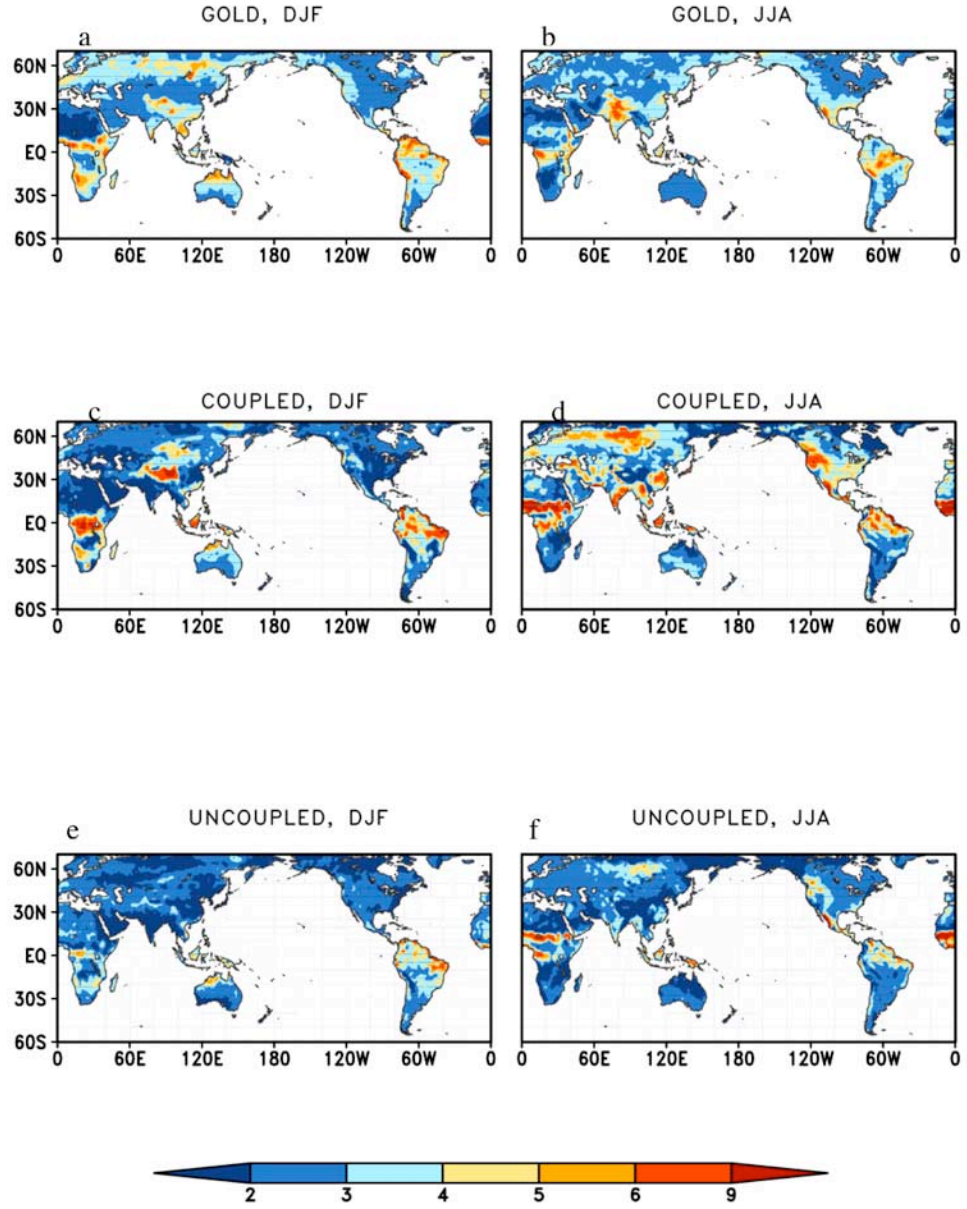

Figure 4. The total number of days when significant correlation (according to t-test at 90% confidence interval) exists over land when evaporation leads precipitation (using daily data) in Boreal winter from (a) GOLD, (c) COUPLED, and (e) UNCOUPLED and in Boreal summer from (b) GOLD, (d) COUPLED, and (f) UNCOUPLED simulations. The units are in days.

[9] An equally relevant aspect of the change in the length of the decorrelation time of daily summer monsoon rainfall is related to the land-atmosphere feedback described in the following sub-section.

3.2. Land Feedback

[10] The Global Land-Atmosphere Coupling Experiment (GLACE) [*Koster et al.*, 2006; *Guo et al.*, 2006] pinpointed to "hotspots" over Africa, central North America and India where multiple models showed robust land-atmosphere coupling. It is contended, based on GLACE results that the differences between the two model simulations shown here are a result of the added contribution of the land surface evaporation feedback on the precipitation. This part of the land-atmosphere feedback is described to be uncertain [*Koster et al.*, 2003]. This is partly because observations are limited. Furthermore, it is extremely difficult to extricate the causality between the two variables that mutually influence each other. A common approach in the past has been to compare two AGCM simulations, one being the control and the other in which the land-feedback to atmosphere is artificially shut off [*Koster et al.*, 2003]. However, in a coupled ocean-land-atmosphere framework the plausibility of SST's changing due to "no land feedback" can defeat the purpose of isolating the contribution of the land feedback to climate anomalies. In this study we shall therefore resort to diagnostics that will serve to support at least qualitatively the idea of land-atmosphere feedback on continental scale as an important contributor to the divergence of the solutions between the COUPLED and UNCOUPLED simulations.

[11] In Figure 3 following *Koster et al.* [2003], the correlation of twice-removed triad precipitation from GOLD, COUPLED and UNCOUPLED simulations are shown. In effect this shows the average of the correlations between precipitation of one triad (say days 1–3) with the precipitation two triads later (say days 6–9) in a given season. Presumably, if land-atmosphere feedback contributes to prolonging rainy or dry periods then this should be reflected in these temporal correlations. In Figure 3a the GOLD analysis indicates significant correlations over northern Australia, parts of tropical South America and Africa. The COUPLED simulation (Figure 3c) captures this correlation fairly well (with the exception over northern Australia) while the UNCOUPLED simulation (Figure 3e) shows relatively very weak correlations over these areas. Similarly, in the Boreal summer the COUPLED simulation (Figure 3d) and GOLD data (Figure 3b) indicate significant correlations over the Asian monsoon regions of India and China, the north American monsoon region of southwest US and Mexico and over the west African monsoon region suggesting a strong land-atmosphere feedback mechanism following *Koster et al.* [2003]. The UNCOUPLED simulation (Figure 3f) shows a far less resemblance to GOLD (Figure 3b) although, it is able to weakly differentiate the summer monsoon regions.

[12] In Figure 4 the number of contiguous days when (statistically) significant (according to t-test) correlation exists between evaporation and precipitation (with the former leading the latter) is shown for both seasons. Clearly, in Figures 4a–4d, longer lead times are seen over the summer monsoon regions, relative to its winter counterpart in both the GOLD data set and in the COUPLED simulation. This lead-time of the evaporation leading the precipitation by over 4 days in the summer monsoon regions suggests the strong influence of the local evaporative fluxes on extending the memory of the day-to-day precipitation events. It is also consistent with the relatively longer decorrelation time of the daily summer monsoon rainfall (Figure 1). However unlike the COUPLED run, the UNCOUPLED simulation has a shorter lead-time between evaporation and precipitation in the summer, reflecting a weak land-atmosphere feedback (Figures 4e and 4f). But the UNCOUPLED simulation as in the previous figure is able to identify the summer monsoon regions with this metric, albeit weakly.

4. Conclusions

[13] In this study it is shown that all regional monsoons exhibit coupled interactions of the ocean-land-atmosphere. The relatively long auto-decorrelation time of the summer monsoon rainfall is identified as a product of these coupled interactions. It is shown that this feature of the summer monsoon (of its extended memory of daily precipitation) is related to the strong land-atmosphere feedback. However, this feedback is best simulated when air-sea coupling is included in the modeling framework. By inclusion of the air-sea interaction in the modeling system, the propagating sub-seasonal variability is enhanced causing more "on-shore" precipitation. This study provides hope of improving the monsoon prediction skills as the community slowly moves towards an era of using coupled ocean-land-atmosphere modeling framework for prediction at all spatio-temporal scales.

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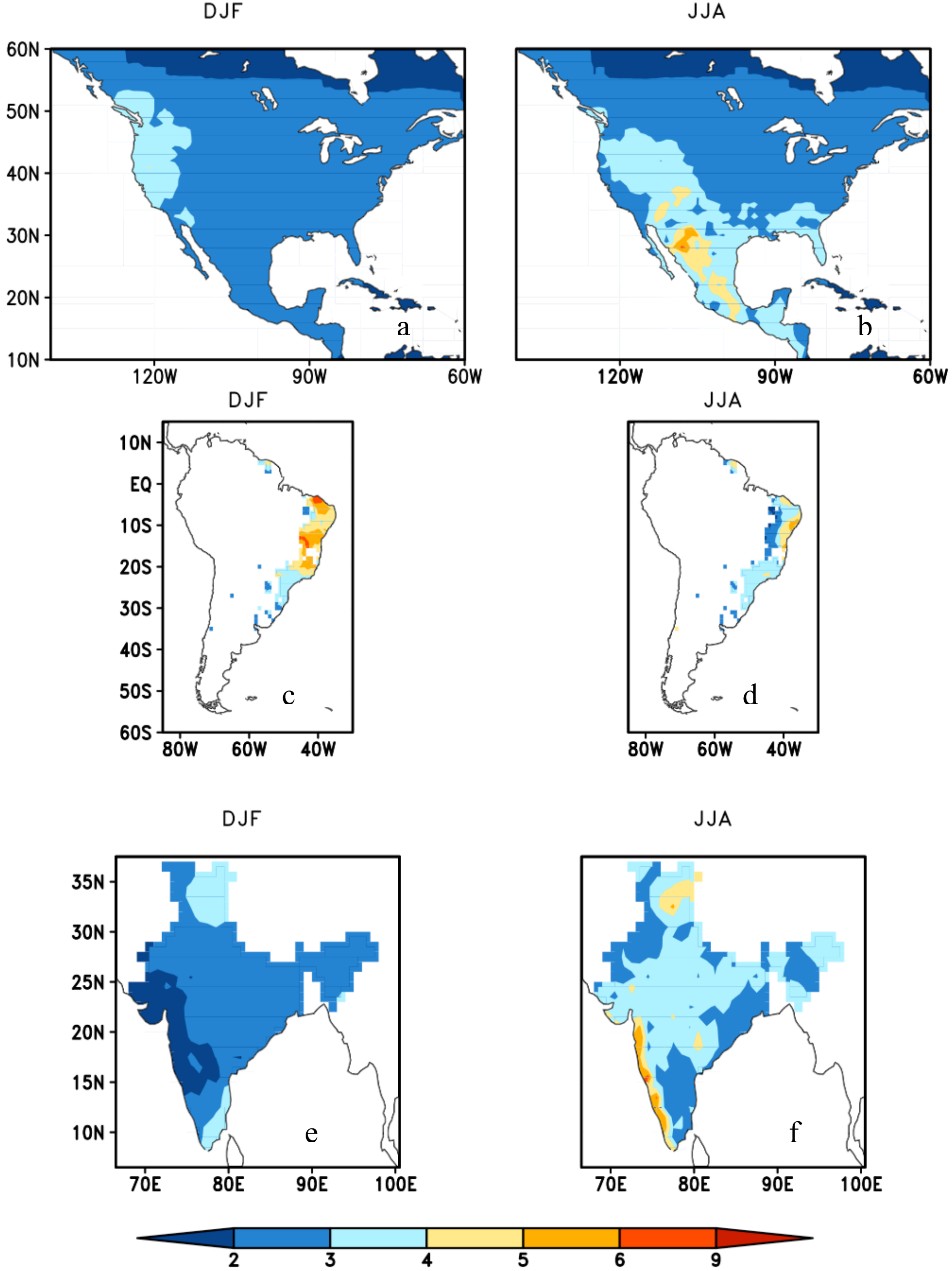
Supplementary Material



Decorrelation time of daily precipitation for Boreal winter and summer seasons from gridded rain gauge observations over the a, b) US and Mexico at 1^0 resolution covering a period from 1948-2001 (Higgins et al., 2004), c, d) over eastern Brazil at 1^0 resolution covering a period from 1940-2005 (Liebmann and Allured, 2005) and e, f) over India at 1^0 resolution covering a period from 1951-2003 (Rajeevan et al. 2006).

Model Description

The Center for Ocean-Land-Atmosphere Studies (COLA) coupled climate model (Misra et al. 2007, Misra and Marx 2007) is used in this study. A brief outline of the COLA AGCM is provided in Table 1. Similarly, a brief outline of the OGCM is provided in Table 2. The COLA AGCM is run at T62 spectral truncation with 28 sigma levels. The OGCM has a uniform zonal resolution of 1.5^0 while the meridional resolution is 0.5^0 between 10^0S and 10^0N gradually increasing to 1.5^0 at 30^0N and 30^0S and fixed at 1.5^0 in the extratropics.

Table 1: A brief outline of the COLA AGCM V3.2

	Feature	**Reference**
1	Convection	(Moorthi and Suarez 1992; Bacmeister et al. 2000)
2	Planetary boundary layer	Hong and Pan (1996)
3	Radiation	Collins et al. 2006
4	Land Surface	Xue et al. 1996; Dirmeyer and Zeng (1999)
5	Diagnostic clouds and optical properties	Kiehl et al. 1998

Table 2: A brief outline of the OGCM (MOM3.0) of the COLA coupled model

	Feature	**Reference**
1	Vertical mixing	Large et al. (1994)
2	Momentum mixing	Smagorinsky (1963)
3	Tracer mixing	Redi (1982)
4	Quasi adiabatic stirring	Gent and McWilliams (1990)

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